

# (12) UK Patent Application (19) GB (11) 2 171 514 A

(43) Application published 28 Aug 1986

(21) Application No 8603692

(22) Date of filing 14 Feb 1986

(30) Priority data

(31) 8504730

(32) 23 Feb 1985

(33) GB

(71) Applicant

STC plc (United Kingdom),

190 Strand, London WC2R 1DU

(72) Inventors

Philip Exance

Roger Edward Jones

(74) Agent and/or Address for Service

M C Dennis,

STC Patents, Edinburgh Way, Harlow, Essex CM20 2SH

(51) INT CL<sup>4</sup>

G01R 33/022 33/032

(52) Domestic classification (Edition H):

G1A A7 C12 C13 C6 C8 CE D10 D4 G17 G18 G7 G8 P10  
P18 P6 R7 S4 S5 T15 T28 T5 T7 T9  
U1S 1252 1833 G1A

(56) Documents cited

None

(58) Field of search

G1A

Selected US specifications from IPC sub-class G01R

## (54) Magnetic gradient detector and method

(57) Two portions (B,C) of one arm of an optical fibre Mach-Zehnder interferometer are magnetically sensitised and each has applied thereto an a.c. bias field at a respective different frequency ( $\omega_1$ ,  $\omega_2$ ). One portion (A) of the other arm of the interferometer is magnetically sensitised and has two a.c. bias fields applied thereto, each at one of the different frequencies ( $\omega_1$ ,  $\omega_2$ ). The fields for portions A and C are aligned with a first direction (x) whereas those for A and B are parallel, A and B being separated in a second direction (y). The detected output of the interferometer at frequency  $\omega_1$  is related to the magnetic gradient in the y direction, whereas the detected output at frequency  $\omega_2$  is related to the magnetic gradient in the x direction. Thus using two bias frequencies allows one interferometer to be used to detect two gradients.

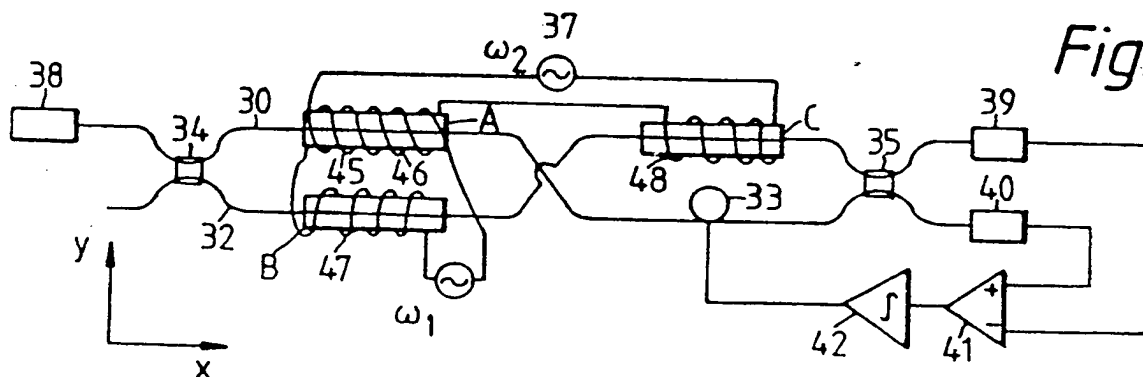
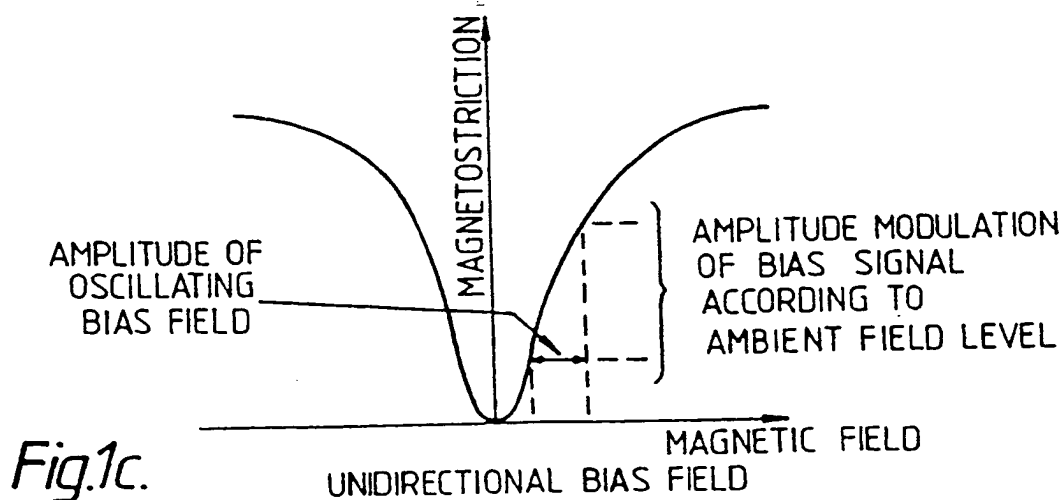
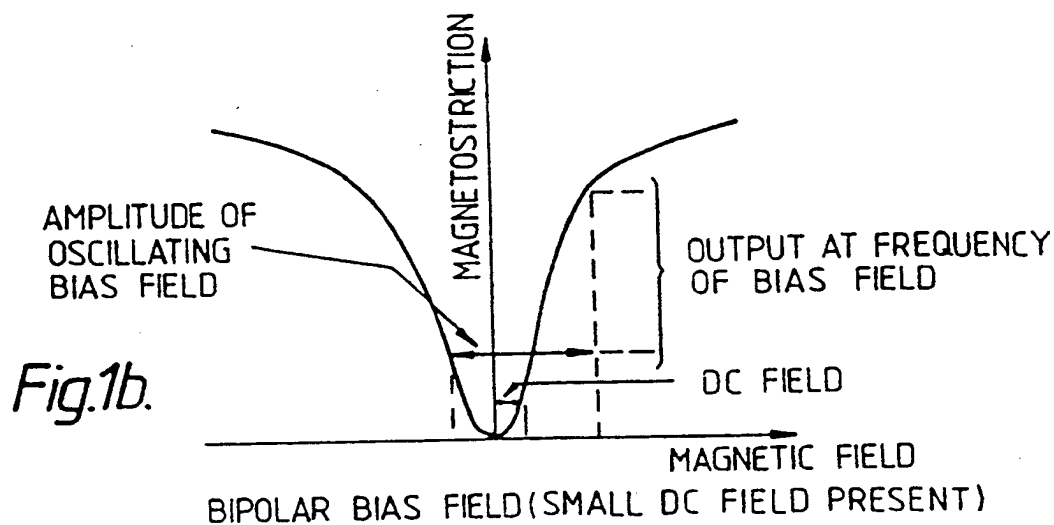
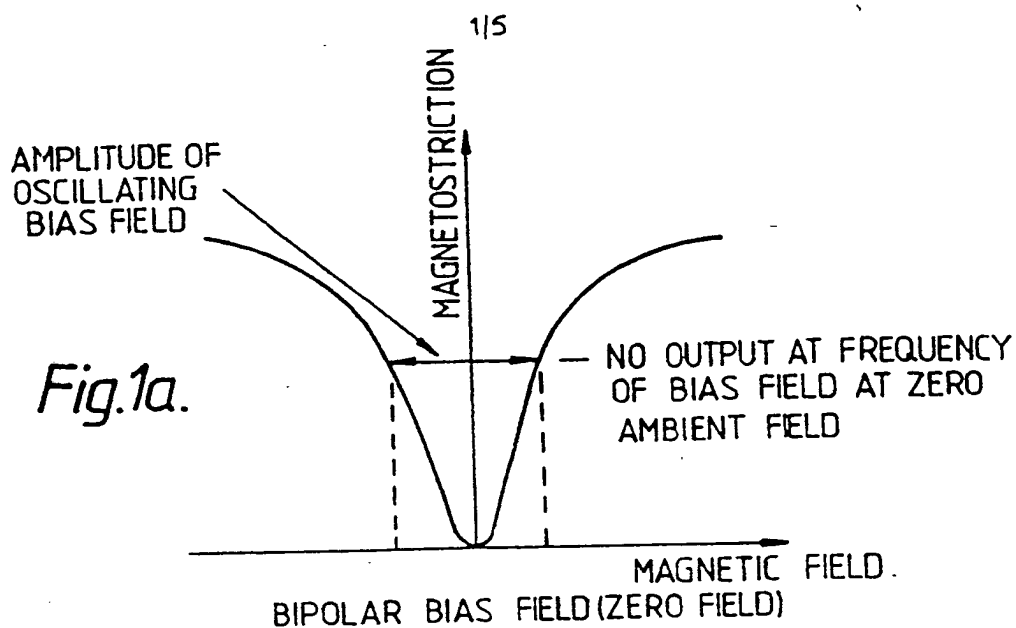


Fig. 8.

GB2171514 A



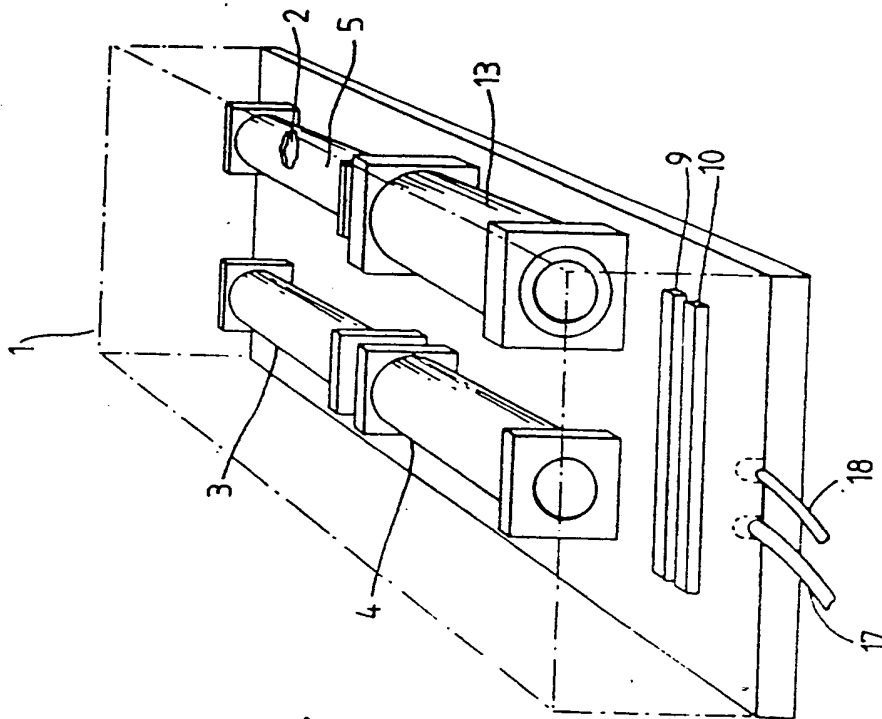
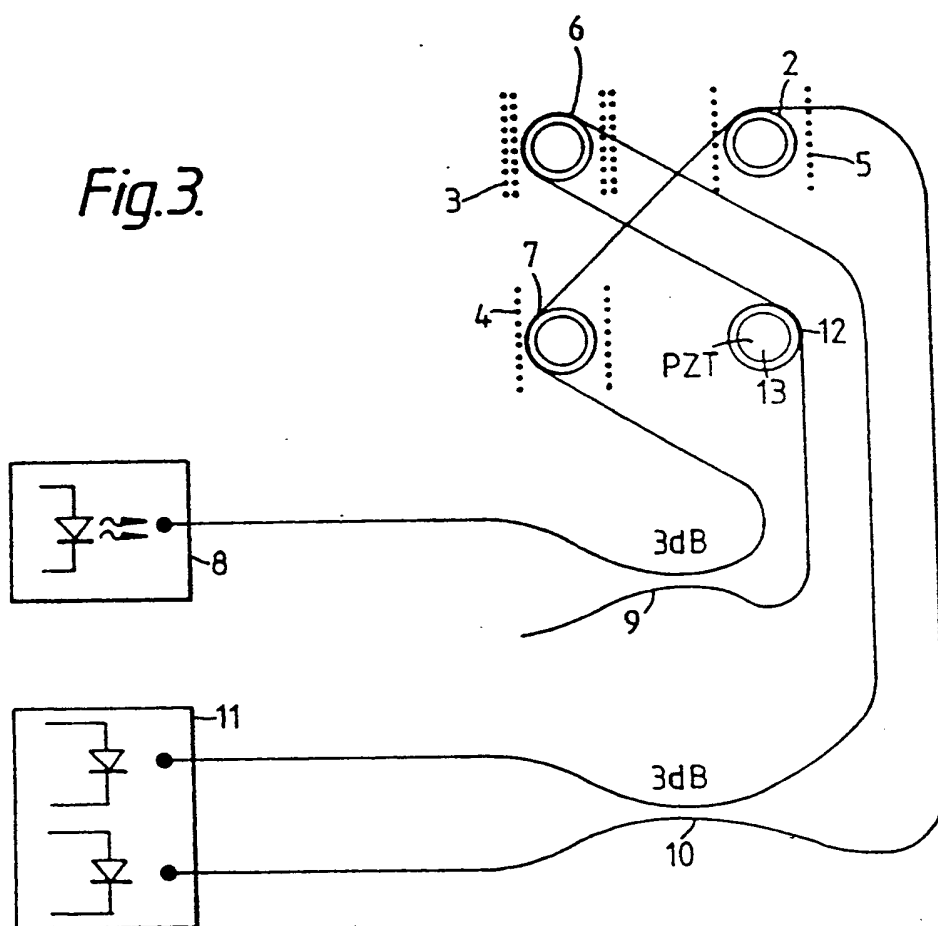
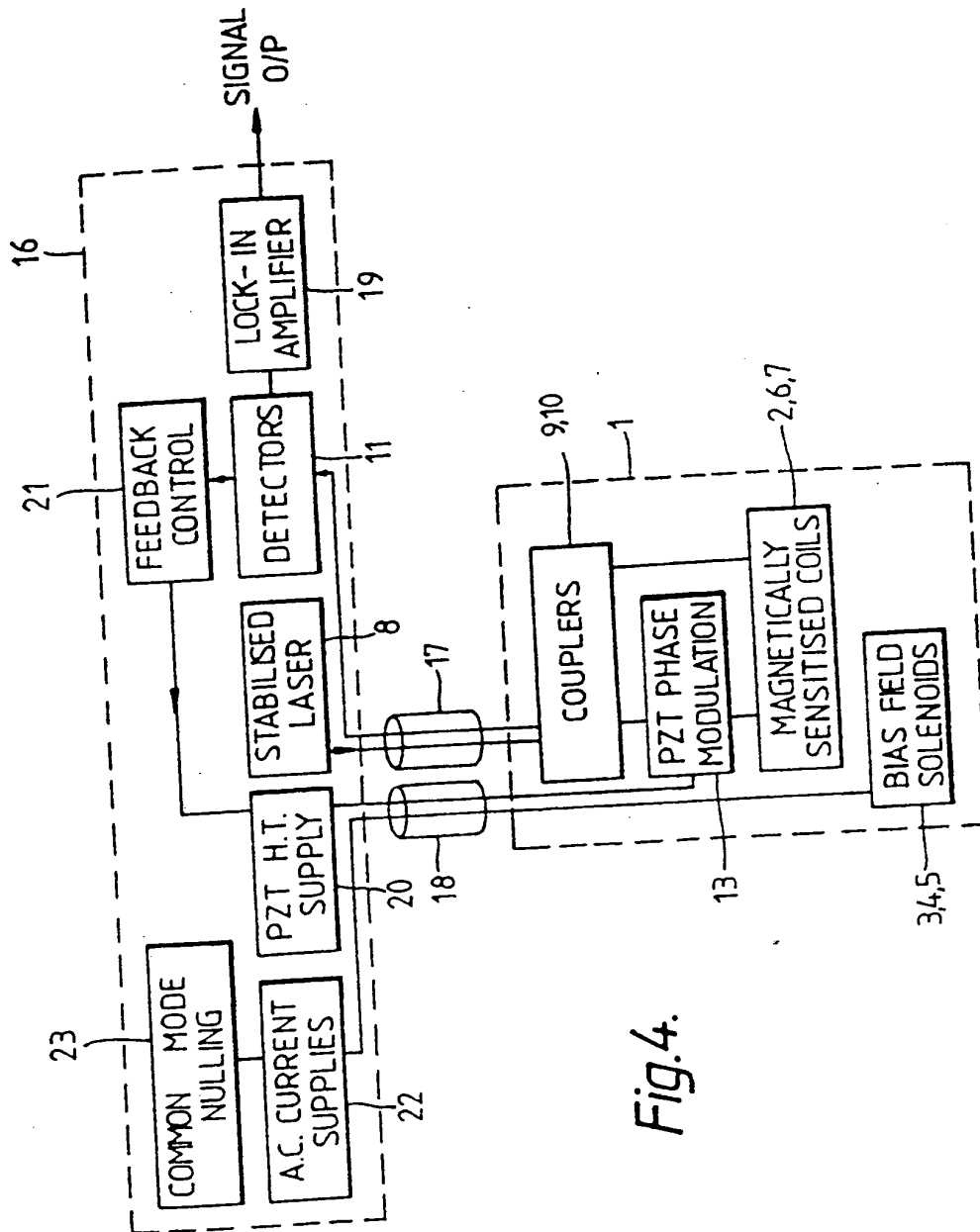
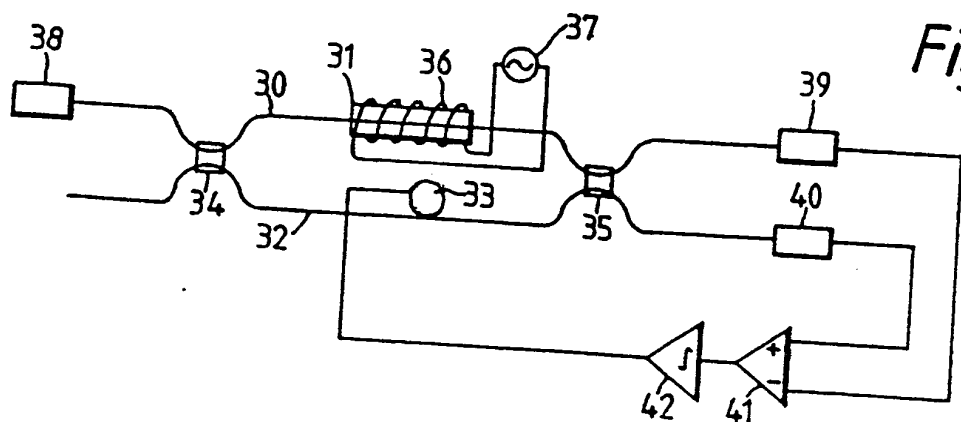


Fig. 2.

*Fig.3.*





*Fig.5.*

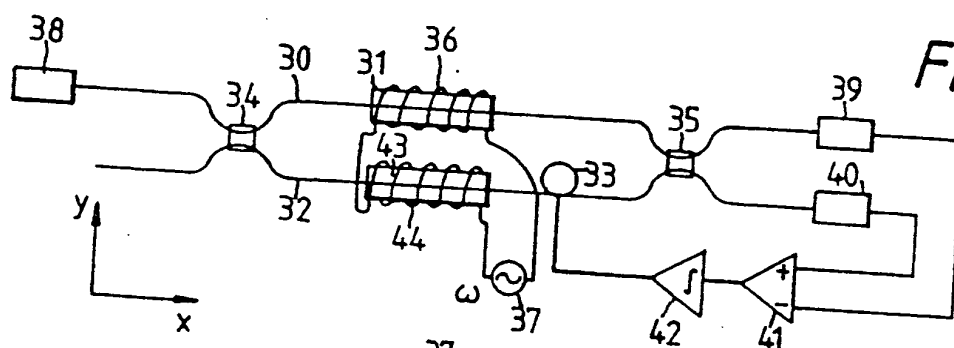
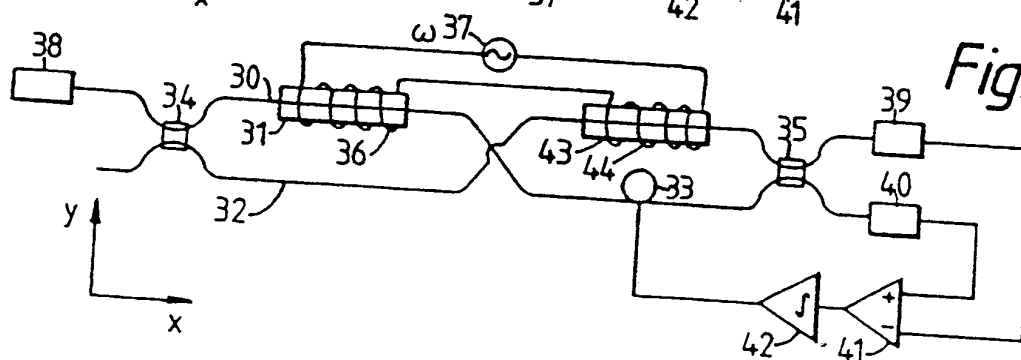
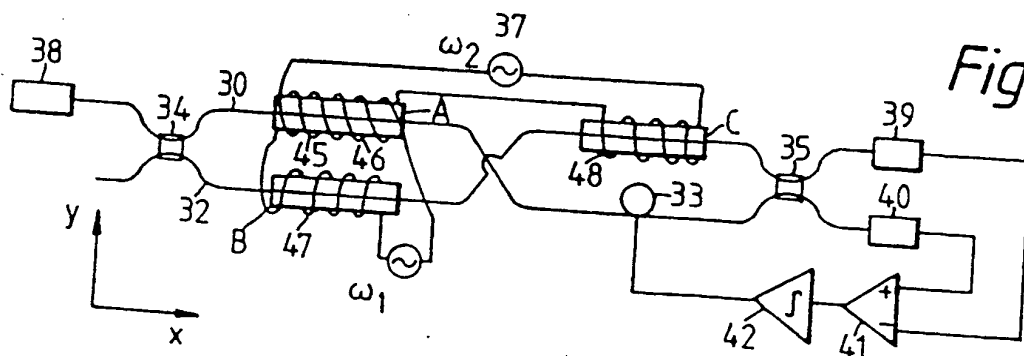


Fig.6.



*Fig.7.*



*Fig.8.*

## SPECIFICATION

### Magnetic gradient detection

- 5 This invention relates to magnetic gradient detection and in particular to an optical fibre magnetic gradient detector.

- Magnetic anomaly detection (MAD) systems are used for submarine detection and geophysical survey systems. A convenient way of detecting an anomaly is to measure the gradient of the magnetic field. The Earth's field will be distorted by an anomaly so that a gradient of the ambient field results. Our co-pending Applications No. 8504729 (Serial No. ) (P. Extance-R.E. Jones 18-18) and No. 8504731 (Serial No. ) (P. Extance-R.E. Jones 20-20) describe various gradient detector schemes whereas the present application relates to a particular form of fibre optic magnetic gradient detector.

- It is well known that when certain materials are placed in a magnetic field their length changes. Such materials are said to be magnetostrictive. For small fields of magnitude  $H$ , the change in length is proportional to  $H^2$ . If an optical fibre is bonded to or coated with a magnetostrictive material, or coiled around a magnetostrictive former, then the application of a magnetic field causes a change in the optical path length within the fibre, this being due to a combination of both length and refractive index changes. This path length change can be measured by incorporating the magnetically sensitised fibre in one arm of an all-fibre Mach-Zehnder interferometer and hence the magnetic field can be determined. The interferometric configuration means that small changes in fibre length may be readily detected; it is well documented that optical path length changes as small as  $10^{-6}$  of a wavelength, i.e.  $10^{-12}$ m may be detected. Minimum detectable fields of 1 gamma per metre of sensitised fibre have been demonstrated. Because such small length changes may be easily caused by effects other than the desired magnetostrictive one, such as temperature and pressure, the interferometer suffers from cross-sensitivity to other parameters. Since the frequency range of interest for a particular magnetic sensor is in the region 0.01 to 1Hz, clearly the low frequency noise due to environmental fluctuations will obscure small signals. Various other parameters of the interferometric system also change on a similar time scale, such as polarisation fluctuations in the fibres and these also obscure the magnetic signal.

- In conventional all-fibre Mach-Zehnder interferometers the detection of a.c. magnetic signals, where the most sensitive measurements to date have been achieved, is usually accomplished using active homodyne demodulation which maintains the interferometer at quadrature by compensating for low frequency phase

- variations such as those which arise from temperature. The system maintains maximum interferometric sensitivity to a.c. magnetic fields beyond the frequency range of the compensation. This signal recovery system relies on the amplitude of the magnetic signal being greater than that of the interferometer  $1/f$  noise at the chosen signal frequency. DC magnetic field detection is a more difficult problem because the signal is in the same frequency band as the  $1/f$  noise and one has no prior knowledge of the signal waveform. One conventional interferometer is that disclosed by Koo K.P. et al in "A Fiber Optic DC Magnetometer" IEEE J. Lightwave Technology, LT-1, 3, pp 524-5, 1983. This dc magnetometer uses an all-fibre Mach-Zehnder with a diode laser source and a passive demodulation scheme with a  $(3 \times 3)$  coupler. A coil was wound around a metallic glass (magnetostrictive material) sensitised arm, and an a.c. biasing field was applied thereby. A spectrum analyser was used to measure signals at the output of the interferometer which were at the frequency of the alternating bias field. Upon the application of d.c. bias fields, simulating d.c. fields to be detected, the output was shown to be linear up to an applied field of 1 Oe and by comparing the signal due to a known field with the noise of the system the sensitivity was determined to the  $10^{-10}$  tesla  $m^{-1}$  in a 1Hz bandwidth. In a magnetic gradient detector both arms of a Mach-Zehnder interferometer are sensitised with magnetostrictive material and they are separated by a desired baseline spacing. Koo K.P. and Sigel G.H. describe a magnetic gradient detector in "A Fibre-Optic magnetic gradiometer" IEEE J. Lightwave Technology, LT-1, 3, p 509, 1983. Both arms of the interferometer were sensitised to the same degree and the device responded to difference in field between the two arms. The optical source and demodulation scheme of the interferometer were the same as described in the first mentioned paper, but there were two sets of excitation coils providing the alternating bias fields, both operating at the same frequency. The magnitudes and phases of the a.c. and d.c. components of these fields were carefully balanced in order to remove any common mode effect caused by variations in the ambient field level. The ability to carry out this fine tuning electrically rather than mechanically altering the coupling between the fibre and the metallic glass is particularly advantageous. The gradient sensitivity that can be achieved is similar to that of the simple total field sensor i.e.  $10^{-10}$  tesla  $m^{-1}$  with a baseline spacing of 0.1m.

- According to one aspect of the present invention there is provided an optical fibre magnetic gradient detector which comprises first and second optical fibres arranged as the arms of an optical fibre Mach-Zehnder interferometer and which is adapted to detect two or

more magnetic gradients by virtue of the relative arrangement of magnetically sensitised portions of the fibres and the provision of bias fields, for said portions, which oscillate at two or more, respectively, bias frequencies.

- According to another aspect of the present invention there is provided a method of detecting two or more magnetic gradients with first and second optical fibres arranged as the arms of an optical fibre Mach-Zehnder interferometer and having magnetically sensitised portions, comprising the steps of providing bias fields at the sensitised portions which oscillate at two or more, respectively, bias frequencies and disposing the sensitised portions relative to one another whereby they can respond to the two or more magnetic gradients to be detected.

- Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figs. 1a, b and c indicate detection schemes for d.c. fields;

- Figs. 2 illustrates, schematically, the sensor head of a fibre optic magnetic gradient detector arranged to detect two magnetic gradients at right angles to one another;

Fig. 3 illustrates, schematically, the optical system of the detector of Fig. 2;

- Fig. 4 illustrates a systems diagram of the detector of Figs. 2 and 3;

Fig. 5 illustrates an optical fibre magnetometer;

- Fig. 6 illustrates one configuration of an optical fibre magnetic gradient detector;

Fig. 7 illustrates an alternative configuration of optical fibre magnetic gradient detector, and

- Fig. 8 illustrates the detector of Fig. 2 when drawn in the same format as Figs. 5 to 7.

- In order to obtain magnetic field measurements with the quoted sensitivity at low frequencies using an all-fibre Mach-Zehnder interferometer, it is necessary to carry out processing to remove the signal from the 1/f noise. The magnetostriction versus applied field curve is a non-linear, even function of magnetic field (Fig. 1a - solid line), and by application of a suitable alternating bias field (Fig. 1b), the level of the ambient d.c. field may be deduced by examining the response at odd harmonics of the excitation (bias) frequency, in particular the first, or fundamental harmonic. The use of an alternating bias field means that the system is not passive, as electrical connections are needed to produce the bias field which is generated by passing an a.c. current through a coil in which the sensing fibre is disposed, for example. As a result it is not necessary to go to great lengths to achieve a truly passive demodulation scheme for the interferometer which is instead controlled by means of a piezoelectric phase modulator in one arm. This simplifies the support circuitry required and reduces the system

noise. The d.c. magnetic signal is measured at a frequency where the amplitude of the 1/f noise is much smaller by an approach using active homodyne demodulation with the piezoelectric phase modulator maintaining quadrature.

- Reference to Fig. 1a shows that for small values of applied field the magnetostriction versus magnetic field curve is parabolic. The application of an oscillatory bias field will, therefore, result in a magnetostrictive response ( $\lambda$ ) given by the product of this bias field and the gradient of the curve

$$\lambda = k \cdot H^2$$

$$d(\lambda)/dH = 2k \cdot H$$

- This is linear in  $\lambda$ . Hence the magnetostrictive output at the bias frequency is directly proportional to the ambient field. A further feature of this detection system is that it can provide information about the sign of the d.c. field, whereas a simple magnetostrictive sensor (without a bias), because of the square-law response, can only give an indication of the magnitude of the field. The alternating bias field can be at any frequency which is more than twice that of the highest measurement frequency of interest, a typical value being 1kHz. This is high enough to extract the signal of interest from the troublesome 1/f noise, while still giving good response from the magnetostrictive material (metallic glasses operate at frequencies up to approximately 10kHz). Noise sources that are removed by this means include environmental perturbation of the optical path length along the fibres and, to first order, fluctuations in the state of polarisation of light transmitted along the fibre. Fig. 1(b) illustrates the operation of the detection scheme of Fig. 1a when a small d.c. field is present. Fig. 1c illustrates the operation of an alternative d.c. field detection scheme, this time employing a unidirectional oscillating bias field rather than the bipolar bias fields of Figs. 1a and b.

- A magnetic gradient detector consisting of an optical detector module and a separate control electronics module may have advantages by way of facilitating their relative disposal in use, however if so required the detector and control electronics may be integral. A sensor head (optical detector) 1 is shown schematically in Fig. 2 and is based on an all-fibre Mach-Zehnder interferometer with both arms magnetically sensitive. Coils (planar and horizontal) of sensitised optical fibre, such as coil 2, are located inside solenoids 3, 4 and 5 which provide the necessary oscillating bias fields for the d.c. detection technique. There is an optical fibre coil 2 in solenoid 5, an optical fibre coil 6 (not shown in Fig. 2) in solenoid 3, which has two separate windings, and an optical fibre coil 7 (not shown in Fig. 2) in solenoid 4. The design of the optical sys-



tem is shown in Fig.3. One arm of the interferometer, which can be considered a reference arm, includes only one coil of sensitised optical fibre, that is coil 6 which is disposed in solenoid 3. The coils of sensitised fibre 2 and 7 are connected in series in the other signal arm of the interferometer. The output of a stabilised laser 8 is applied to both arms of the interferometer via a 3dB input coupler 9.

The output optical signals are applied to a detector means 11 via a 3dB output coupler 10. The component of magnetic field to be measured is that directed along the axis of the solenoids 3 and 4. Coils 6 and 7 thus give the gradient of the field along its own axis and coils 6 and 2 give the gradient of the field along an axis perpendicular to that of the field component. The resultant optical signal are multiplexed onto the same interferometer by taking advantage of the d.c. detection technique whereby a signal of interest is modulated onto a carrier. This enables one sensor head to measure two gradients simultaneously. Operation of the detector will be described further hereinafter with reference to Figs.5, 6 and 7.

To obtain maximum benefit from the detection scheme, digitally generated sinewave current sources with minimal harmonic content are employed as the sources for the bias field solenoids. Thus the crosstalk between the two channels is minimised and the accuracy of the first harmonic signal is maximised, it being the first harmonic component of the photodetector output which is increased in proportion to the magnitude of the gradient of the magnetic field. The arm including sensitised coil 6 also includes an unsensitised coil 12, which coil 12 is disposed around a PZT cylinder 13 constituting the above mentioned piezoelectric phase modulator. Fig.4 shows a block diagram of the complete system. Block 1 comprises the sensor head (optical detector module) whereas block 16 comprises a control electronics module. The blocks are interconnected by an optical cable 17 and an electrical cable 18. The block 1 includes the elements of Fig. 2 namely the couplers 9 and 10, the PZT phase modulator 13 with its fibre coil 12, the magnetically sensitised coils 2, 6 and 7 and the bias field solenoids 3, 4 and 5. The block 16 includes the stabilised laser 8, the detector means 11, a lock-in amplifier 19 coupled to the detector means output, a PZT H.T. supply 20, which is controlled by the detector means 11 via a feedback control 21, and a.c. current supplies 22, for the bias field solenoids, with a common mode nulling means 23. With d.c. magnetic field signals in the frequency range 0.03 to 1Hz, for example, maximum sensitivity is achieved for that range due to the large integration time available for the signal by the lock-in amplifier 19. For the detection of higher frequency signals spectrum analysis may be preferable, however the signal to

noise ratio available for this mode of data recovery is inferior to that from a lock-in amplifier system.

The all-fibre Mach-Zehnder interferometer is constructed from single mode fibre and fused all-fibre 3dB couplers are preferable. Fibre tails from the various components are preferably fusion spliced together so that no micropositioners or bulk optical components are required and resulting in an extremely rugged system. The laser light source 8 may be a single frequency laser diode operating at 0.85 micrometres or 1.3 micrometres wavelength, the detector means being chosen accordingly. Semiconductor diode lasers have the advantage of small size, modest power supply requirements and ruggedness, but for interferometry they are inferior to gas lasers in their coherence length and output wavelength stability. It is, however, possible to stabilise the output wavelength using an all-fibre Fabry-Perot cavity to lock it, attention is directed in this respect to our co-pending Application No.8401143 (Serial No. ) (R.E. Jones-R.H. Pratt 5-1). The stabilised laser 8 also includes means for controlling the temperature of its mount, such as by means of a Peltier cooler and thermistor module.

Instead of employing the sensor head of Fig. 2, that is optical detector module of block 1 of Fig.4 with the control electronics block 16 including the lock-in amplifier 19 or a spectrum analyser to provide a measure of magnetic field gradient, a known field gradient may be applied, for example by means of Helmholtz coils, so that the gradient to be measured is cancelled, the current in the coils then providing a measure of the gradient.

The operation of the two gradient detector of Figs.2 to 4 will now be discussed in greater detail with reference first to Fig.5 which shows, schematically, a single optical fibre magnetometer interferometer comprising an optical fibre 30 a portion of which is magnetically sensitised by a magnetostrictive element 31, an optical fibre 32 comprising a reference fibre with a PZT phase modulator 33 associated therewith, the fibres being coupled by 3dB couplers 34 and 35. The magnetostrictive element 31 is disposed within a coil 36 coupled to a supply source 37 which supplies an a.c. bias field at frequency  $\omega$ . The output of a laser 38 is applied to one optical fibre and to the interferometer comprised by the two optical fibre arms 30 and 32. The interferometer outputs are detected by detectors 39 and 40, whose outputs as well as indicating the magnetic fields are employed to control the phase modulator 33 via operational amplifier 41 and integrator 42.

If the magnetostrictive element 31 is subjected both to the field of interest (the d.c. field to be measured) and the a.c. bias field at frequency  $\omega$ , then the non-linear characteristics of the magnetostrictive material will

